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Using Quality Function Deployment and Analytical Hierarchy Process for material selection of Body-In-White

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ABSTRACT

Presented manuscript discusses the usage of multi-attribute decision making tools to assist in the material selection for vehicular structures; mainly the automotive Body-In-White (BiW) panels at the conceptual design stage using Quality Function Deployment (QFD) and Analytical Hierarchy Process (AHP). The main advantage of using QFD and AHP is their abilities to rank choices in the order of their effectiveness in meeting the functional objective. AHP discriminates between competing options where interrelated objectives need to be met; AHP is based on straightforward mathematical formulations. QFD on the other side is a customer focused method that usually starts by collecting customer needs and tries to integrate these needs into the product. In this study, following classes of engineering materials are analyzed; forming grade Bake Harden-able steel (BH), Dual Phase steel (DP), High Strength Low Alloy Steel (HSLA), Martenistic steel, Aluminum 5xxx, 6xxx sheets, Magnesium sheets, Titanium sheets, Carbon Fiber Reinforced Plastic (CFRP) and High Density Polyethylene (HDPE). The presented study showed that the different grades of steel gained the first ranks in the selection process for almost most of the BiW panels; however other alternatives could work in trade-off with cost and manufacturability.

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1. Introduction

New trends in vehicle light-weighting not only aim at enhancing the vehicle fuel efficiency, but also at improving its driving performance in addition to lowering its emissions [1]. Weight saving might be achieved through replacing current high density materials such as steel, in chassis and suspension, and other power-train and driveline vehicular sub-systems with lightweight to achieve small weight savings. However, significant improvements in vehicle efficiency in terms of the mile per gallon will require larger reductions in the vehicle weight. To quantitatively describe the relationship between the vehicle weight and its fuel efficiency, several correlations have been proposed and are listed through

$$MPG = 895.24\ (mass^{-0.463}) \tag{1}$$

$$MPG = 8627.4\ (mass^{-0.74584}) \tag{2}$$

$$mass = 2.015 \times FE^2 - 194.85 \times FE + 6375.54 \tag{3}$$

where the *MPG* is the mile per gallon and the *mass* is the curb weight in Lbs, while the *FE* is the fuel economy.

Inspecting these equations one can conclude that in average a weight reduction of 10% of the total vehicle curb weight can only lead to about 5% improvement in the fuel efficiency. That means that major weight reductions (>10%) are required to have any tangible effects on the vehicle fuel consumption. Automotive designers typically target the vehicle main structure or Body-In-White BiW for weight reduction activities because; any weight savings from the vehicle interior trim affects its comfort options (e.g. motorized seats, etc.), while any weight savings from the power-train imparts the vehicle mobility function, both of these effects hinder the vehicle marketability. Fig. 1 displays the weight distribution of a typical sedan, with the BiW weight comprises around 20–25% of the total vehicle curb weight.

The direct replacement of steel structures with other less dense materials has been the usual route for earlier light weight engineering efforts, especially using more Aluminum in the BiW. However this trend is challenged by the following: (a) the complexity associated in forming aluminum using the standard press based stamping, which limits the minimum bending radius to panel thickness ratio hence limiting the geometries, and design features which in turn affect the vehicle styling and limiting the use of

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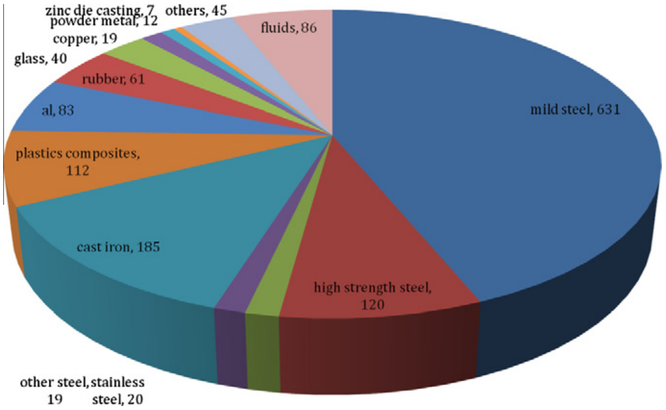

Fig. 1. Material distribution of total vehicle curb weight.

aluminum to flat or semi-flat panels as in the hood. Even though some OEMs have used space frame platforms to facilitate the use of aluminum in the form of extrusions and tubes as in the Audi A3 platform and the Rolls Royce, still the space frame is not easily manufactured for high volume vehicles due to the high manual work-content associated in its joining process. (b) Aluminum is weaker than steel and its Young's modulus is almost 1/3 that of steel affecting its dent resistance and stiffness negatively, respectively. To provide a quantitative example, to replace a steel panel with aluminum while conserving the a panel torsional stiffness requires the designers to match the panel thicknesses based on $\frac{t_{\mathrm{Al}}}{t_{steel}} = \frac{E_{steel}}{E_{\mathrm{Al}}} = 3$, which not only neutralizes the weight reduction achieved but also complicates the forming process. Additionally (c) the introduction of new steel grades with higher strengths as the Advanced High Strength Steels, AHSS, which include; the Transformation Induced Plasticity, TRIP, Dual Phase, DP steels, allow designers to design steel panels with thinner thicknesses allowing for further weight savings. Lastly, (d) the high cost of aluminum (almost four times that of mild steel) limits its wide use in vehicular structures [2]. Fig. 2 displays the trends in the material usage for vehicles; indicating that the development of new steel grades have revived the use of steel for automobile bodies. However at the same time some automotive Original Equipment Manufacturers, OEMs have started to use some integrated metrics to better evaluate the use of light weight materials in their vehicles some of these metrics include the cost added per unit weight saved as in $/kg$_{saved}$ and the light weight engineering index L used by the BMW group illustrated in

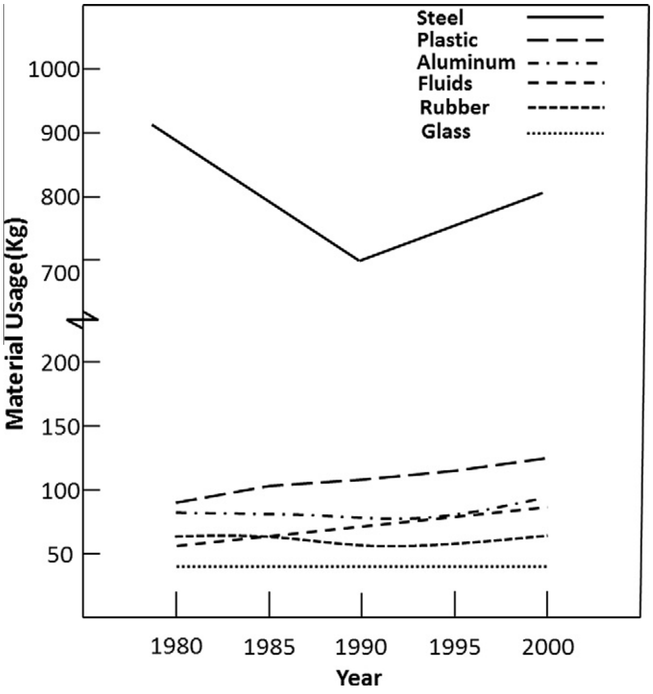

Fig. 2. Material use in the automobile bodies trends.

$$L = \frac{C_{torsional} \times A}{mass} \tag{4}$$

where $C_{torsional}$ is the torsional stiffness of the BiW, and A is the vehicle size, and the *mass* is the mass of the BiW.

The above mentioned facts about using aluminum in automobile bodies motivate the development of a more quantitative material selection process and methodology for the different vehicular structures and panels. The material selection process is recently getting recognized as one of the major branches of the materials science and engineering discipline. It starts by considering all materials and ends by selecting the most appropriate one based on the application functionality and the design constraints. Ashby's work in ranking and material spaces is considered pioneering in the field [3]. This study presents the use of decision making (DM) tools to address the vehicle body design, which have conflicting objectives and multi-attribute constraints. The integration of the material selection principles with decision making methods is a growing trend [4,5], which have in resulted in the Environmental Priorities System (EPS), the Sustainability Decision Support System (SDSS), in addition to material selection using fuzzy logic [6,7].

This study focuses on the use of two specific decision making tools the Quality Function Deployment (QFD), and the Analytical Hierarchy Process (AHP). The ultimate goal of using QFD is to help designers in developing new or existing product or service by incorporating customer needs, the Voice of the Customer (VOC), into engineering characteristics for a product or a service. By doing so, the planners can then prioritize each product or service attributes to set the levels needed to achieve such characteristics. However, QFD can be considered a complimentary method for determining how and where priorities are to be assigned in the product development, where the intent is to employ objective procedures in increasing the detailed design throughout the development of the product [8]. Hence the QFD presents a tool that can be used in all engineering stages and can be applied mainly at the conceptual design stage.

A limited number of papers in the open literature discussed the use of QFD to improve and optimize the vehicle body design; among these limited manuscripts, [9] discussed the implementation of a QFD based procedure to quantify and identify improvements in the vehicle door design. Other publication by Banu et al. [10] utilized QFD to the design of car bodywork to determine the priorities and their impacts on the customer satisfaction.

Among the other decision making methods, the AHP has a distinct advantage of combining both qualitative and quantitative approaches [11]. In the qualitative sense, it decomposes an unstructured problem into a systematic decision hierarchy. It then uses a quantitative ranking using numerical ranks and weights in which a pair-wise comparison is employed to determine the local and the global priority weights and finally the overall ranking of proposed alternatives. Byun in [12] used the AHP methodology to select the car model to purchase, where the selection criteria was basically focused on the customer needs more than on design and reliability. Hambali et al. [13] proposed a concept selection model called Concurrent Design Concept Selection and Materials Selection (CDCSMS) to assist designers in selecting the most appropriate design concepts and materials for automotive composite components at the conceptual design stage using the AHP. Eight